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FINAL REPORT

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This investigation has involved the correlation of BATSE-observed solar hard X-ray emission with the characteristics of soft X-ray emitting plasma observed by the *Yohkoh* Bragg Crystal Spectrometers. The goal was to test the hypothesis that localized electron beam heating is the dominant energy transport mechanism in impulsive flares, as formulated in the thick-target electron-heated model of Brown (1973).

If energetic electrons are indeed the primary energy carrier in flares, then we expect two relationships between soft and hard X-rays to hold. First, the power contained in the electrons (reflected in the hard X-ray bremsstrahlung they generate) should be related to the changing thermal energy content of the chromospheric plasma (reflected by the change in soft X-ray emission). This relationship is known as the "Neupert effect" (Neupert 1968, Dennis & Zarro 1993) and can be parameterized by representing the plasma's changing energy content with the change in the amount of mass μ emitting in a given soft X-ray line. That is,

$$I_{\mathrm{hxr}} \sim \dot{\mu}_{\mathrm{sxr}}. \tag{1}$$

The second relationship involves the nature of the plasma's motion in response to heating by the energetic electrons. The electrons' thermalization in the chromosphere constitutes an extremely localized heating. The resulting pressure gradients force the plasma to move away from the site of most intense heating. Since it takes time for these pressure gradients to build, we expect plasma flows (manifested in Doppler-shifted emission in soft X-ray spectral lines) to appear *after* the hard X-ray emission. An analysis of the hydrodynamic equations (Newton, Emslie, & Mariska 1996) yields the following relationship between hard X-ray flux and the second derivative of the plasma's momentum M for typical flare parameters:

$$I_{\mathrm{hxr}} \sim \ddot{M}_{\mathrm{sxr}}. \tag{2}$$

This relationship holds only for impulsive heating on timescales less than 20 seconds. On longer timescales, the correlation quickly disappears as other terms in the heating-momentum relationship become more important.

BATSE's observations of hard X-rays during flares provides half the information necessary to test for these relationships. The soft X-ray spectral lines observed by the BCS provide us with the remaining information required, namely observations of the emitting plasma's motion as can be inferred from Doppler-shifted emission. We therefore have two testable predictions for the electron-dominant model of flare heating: the "Neupert effect" and, on suitably impulsive timescales, the $I_{\rm hxr} \sim \ddot{M}_{\rm sxr}$ relationship.

The information provided by spectral line asymmetry and broadening (effects arising in part from Doppler-shifting) can be used to construct the plasma's line-of-sight velocity distribution and other quantitative measures of motion. This is possible because the observed line is a convolution of emission emitted by a number of plasma 'elements,' each moving with a specified line-of-sight velocity. We employ an innovative inversion, or deconvolution, technique to recover the velocity distributions inherent in the spectral lines (Newton 1996). These line-of-sight velocity distributions are called *velocity differential emission measures*, or VDEMs. From the recovered VDEMs, we may compute the emitting plasma's mass and momentum (Newton et al. 1996), as they are related to the moments of VDEM.

Between 1993-1995, almost 300 solar flares were observed simultaneously by the *CGRO* BATSE experiment and *Yohkoh*. Only 57 of these, however, were sufficiently energetic to trigger BATSE (the hard X-ray flux must exceed 5.5σ in two or more detectors simultaneously on one of three timescales [64, 256, or 1024 ms]). We initially limited our sample to *triggered* flares for which the hard X-ray emission was less than 200 s in duration and in which no data gaps or problems in either instrument were evident. This reduced the number of flares in the sample to 15 C or M-class flares.

For these flares, the VDEMs were computed from the Ca XIX spectral line by deconvolution. Then the total emitting mass μ and plasma momentum M, as well as their temporal derivatives, were computed from VDEM for comparison with the BATSE-observed hard X-ray flux. As outlined in equations (1) and (2), we expect the behavior of $\dot{\mu}$ and $\ddot{M}$ to match the evolution of the hard X-ray flux. To quantify the correspondence between hard X-ray flux and the soft X-ray plasma's behavior we employed the Spearman rank-order (nonparametric) correlation test. Correlation coefficients close to one indicate strong correlation; small probabilities indicate the measurement of a statistically significant correlation result.

In the test for the Neupert relationship, statistically significant, strong correlations between $\dot{\mu}$ and the hard X-ray flux were found in 9 events. An example is shown in Figure 1. Correlation coefficients were all greater than 0.7 and probabilities all less than 4×10^{-5}. One event was consistent with a moderate correlation, and the remaining 5 consistent with weak correlations, although the significance of the measurements was low due to the low flux levels involved and/or the few number of data points available for measurement.

In these 15 flares, the hard X-ray bursts were all longer than 20 s in duration or were preceded by extended low-level flux indicating steady heating. Because the hard X-ray profiles did not conform to the criteria specified for successfully applying the second test, we did not observe any $\ddot{M}$-hard X-ray flux correlations. We did note, however, in a number of cases that the $\ddot{M}$ curves increased as the hard X-ray flux rose above background, before the long timescale destroyed the correlation. We then looked to *untriggered* BATSE flares to find those with hard X-ray bursts that did meet the criteria for the second test (i.e., less than 20 s in duration). There were 21 flares of sufficiently short duration to qualify. We found, however, in examining the BCS data and the corresponding VDEMs that the BCS's limited time resolution (3 s) made it impossible to measure a correlation. Again though, there was qualitative evidence for a correspondence between the plasma quantities and the hard X-ray flux.

In summary, the Neupert relationship is obviously a more robust test than that involving momentum, since the $\ddot{M}$ test is applicable only under restrictive circumstances (short pulse not preceded by significant extended flux). Furthermore, the BCS's limited time resolution inhibits the generation of statistically significant $\ddot{M} \sim I_{\rm hxr}$ measurements. This fact, combined with evidence for the Neupert relationship in only 60% of the cases, prevents us from making a definitive conclusion about electrons as the predominant mechanism of flare heating. We do, however, believe that the tools developed in this investigation, namely VDEM and quantitative measurements of plasma properties (μ and M) from VDEM, are useful tools which will contribute to future investigations.

Part of these findings has been published as "Tests of the Electron-Dominant Model of Flare Heating," in the APS Series monograph, *Observations of Magnetic Reconnection in the Solar Atmosphere*, 1996. A full summary of the results will be submitted to the *The Astrophysical Journal.*

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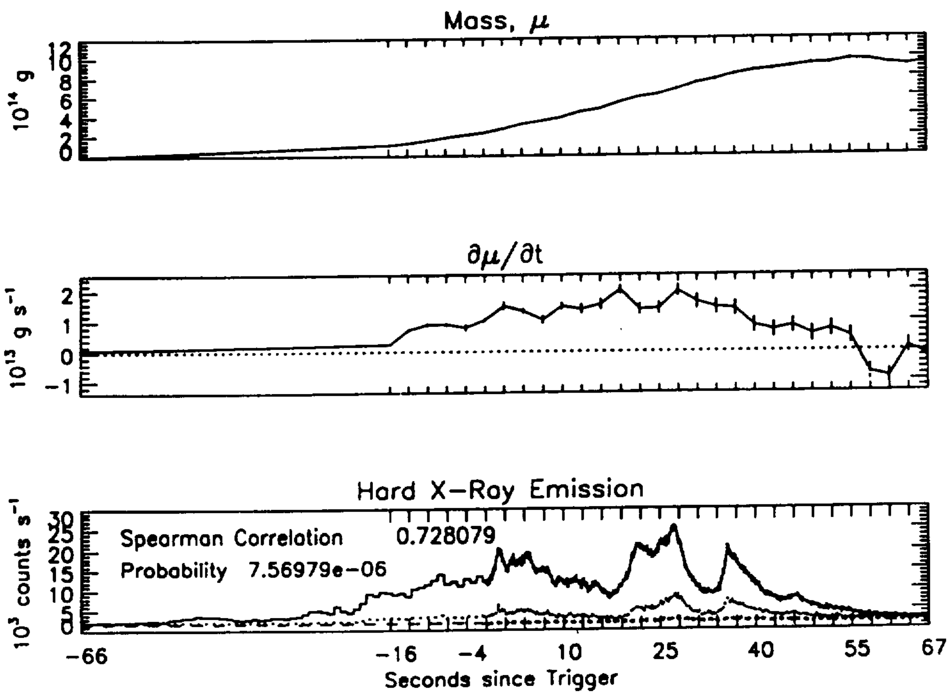

Figure 1 Illustration of the Neupert relationship: strong correlation between $\dot{\mu}$, the change in amount of emitting mass, and observed hard X-ray flux of the 6 April 1993 (UT 23:08) flare